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INITIATION OF EXPLOSIVES BY EXPLODING WIRES III.

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17 MARCH 1964

UNITED STATES NAVAL ORDNANCE LABORATORY, WHITE OAK, MARYLAND

NOLTR 64-2

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INITIATION OF EXPLOSIVES BY EXPLODING WIRES

III. Effect of Wire Diameter on the Initiation of PETN by Exploding Wires

By Howard S. Leopold

ABSTRACT: The effect of wire diameter on the initiation of PETN by exploding platinum wires was investigated. A one microfarad capacitor charged to 2,000 volts was used as the energy source for exploding the wires. The diameter of the wire can be chosen so as to favor time reproducibility of explosion, reliability of effecting detonation, or vigor of the bridgewire output. The wire with the most vigorous shock output when tested in air is not necessarily the most efficient for effecting detonation when PETN is loaded on the wire.
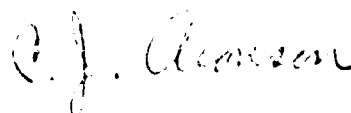
PUBLISHED MAY 1964

INITIATION OF EXPLOSIVES BY EXPLODING WIRES
III. Effect of Wire Diameter on the Initiation of PETN
     by Exploding Wires

This report is Part III of an investigation concerning the
initiation of explosives by exploding wires. The work was
performed under Task RUME-4E000/212-1/F008-08-11 Problem No.
019, Analysis of Explosive Initiation.

The results should be of interest to personnel engaged in
initiation research and the design of exploding bridgewire
ordnance systems.

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or endorsement of these products by the Naval Ordnance Laboratory.

R. E. ODENING
Captain, USN
Commander

C. J. ARONSON
By direction

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INTRODUCTION

1. This is the third report describing experimental results obtained from an investigation on the interaction between an exploding bridgewire and explosives. Previous investigation[1,2] had shown that circuit inductance and resistance should be kept to a minimum for effective initiation of PETN. Also, that the length of a 1-mil diameter platinum wire should be chosen so as to eliminate a definite current dwell period. In addition, it was found that secondary current pulses have little effect on whether or not detonation is produced in the PETN.

2. Bennett[3], and Jones and Gallet[4] have shown that there is an optimum wire diameter for producing the maximum shock in air when a given wire material is exploded by a fixed firing circuit. Our original investigation was started using a platinum wire diameter of 1-mil. This diameter was arbitrarily chosen simply because it was known to explode in nominal lengths with the energy available from a 1-microfarad capacitor charged to 2,000 volts. Energy computations based on the current and voltage waveforms showed that only a small percentage of the energy stored in the capacitor was deposited in the 1-mil diameter wire. The rest of the energy is dissipated in extraneous circuit resistance or left in the capacitor. This indicated that a 1-mil diameter might not represent the best diameter that could be employed. The present investigation was concerned with determining the effect of wire diameter and learning more about the conditions that determine whether or not detonation develops.

ELECTRICAL CIRCUITRY

3. A typical exploding bridgewire firing circuit consists of a one microfarad capacitor charged to 2,000 volts. The actual test circuit used for this investigation shown in Figure 1 is similar to that used for previous studies. The parameters for the test circuit are

$$C = 0.97 \text{ microfarad}$$
$$L = 0.58 \text{ microhenry}$$
$$R = 0.35 \text{ ohm}$$
$$V_o = 2,000 \text{ volts}$$

Methods used for the determination of the circuit parameters are given in references 1 and 2.

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*References are given on page 8

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TEST PROCEDURE

4. The shock output of various diameter platinum bridgewires was first determined in air and then correlated with the ability to effect detonation in PETN. To determine the vigor of the output of the wire explosion, a photographic technique used by Bennett[6] was employed to observe the shock wave and plasma expansion of the wire. The wire was mounted in a holder as shown in Figure 2. The slit image of a smear camera was aligned perpendicularly to the wire. The image of the wire explosion reflected in a mirror provided backlighting for the event. This makes the normally non-luminous shock waves visible. Oscillograms were taken of the current and voltage waveforms concurrent with the smear photograph of the wire expansion. Resistance, power, and energy computations were made from the oscillogram readings.

5. The various diameter bridgewires were then subsequently tested for their ability to effect detonation in PETN. The test fixture and experimental methods described in reference 1 were used for observing the growth of explosion.

EXPERIMENTAL RESULTS

6. Seven different diameters of platinum wire ranging in size from 0.0005- to 0.005-inch were tested, in the fixture shown in Figure 2, to determine the vigor of the wire explosion. The test wire, 0.050-inch long, was soldered to the upper part of the contact pins, suspended in air, and exploded. Selected photographs of the resulting explosions are shown in Figure 3. Only the upper portion of the wire explosion trace was usable because of the reflections from the contact pins which set in almost immediately in the lower portion.

7. The criterion for the vigor of wire explosion was the rate of radial expansion of the shock wave and outer plasma surface. The test results are shown graphically in Figure 4 with each curve representing the average of three shots. The curves were measured for their observable period or for a maximum of 2 microseconds. Previous data obtained with PETN loaded on the wire at a density of 1 g/cm^3 have shown that detonation, when it occurs, starts within one microsecond after the time of wire burst. The vigor of the wire explosion in air, as measured by the radial expansion from the time of wire burst, shows an optimum wire diameter. From the plots in Figure 4 it can be seen that the 0.003-inch diameter wire gives the most vigorous output in air, closely followed by the 0.002 and 0.0015-inch diameters.

8. Another test series was run because of the closeness of the results for the 0.0015, 0.002, and 0.003-inch diameter wires. The platinum wire was mounted flush on a plastic plate. A reflective mirror was not used and only the outer surface of the plasma expansion was observed. The same order of vigor was noted as shown in Figure 5. Each curve represents the average of three shots. The rate of plasma expansion is greater for this series than for the suspended wires. This is expected since the flush mounting limits the expansion region to a 180° arc.

9. It was also observed that the time to wire burst increases with increasing diameter and hence increasing mass. Nash and Olsen[6] have shown that there is a close to linear relationship between the cross sectional area of the wire and the time to burst at constant initial voltage. A close to linear relationship up to the 0.003-inch diameter wire was also observed in our tests. However, a definite deviation was observed with the larger diameters as shown in Figure 6. An examination of the oscillograms shows that the 0.0005, 0.001, 0.0015, and 0.002-inch diameter wires explode on successively higher levels of the first current pulse. The 0.003-inch diameter wire explodes just after the first current peak. Figure 7 shows the explosion loci on an idealized* current pulse. The 0.004-inch diameter wire does not receive enough energy to completely vaporize during the first current pulse, nor is enough energy deposited by the time current ceases to flow. Computations show that enough energy is delivered to vaporize approximately 70% of the wire and bring the remaining 30% to the boiling point. With the 0.005-inch diameter wire, the current ceases to flow after three half cycles. No shock wave is emitted and the wire breaks up into macroscopic molten particles as evidenced by the photographic traces.

10. If it is hypothesized that the vigor of the wire explosion is directly related to the ability of the wire to effect detonation, then a 0.003-inch diameter wire should be optimum for the circuit parameters employed. The ability of the wire to effect detonation in an explosive should decrease as the vigor of the wire explosion decreases. This was tested using PETN and gradually decreasing the probability of detonation by increasing the loading density of the PETN. A series of test shots was run to determine the optimum wire diameter for detonation. This method eliminated any change in the electrical parameters. The results in Table 1 show some agreement between the vigor of the wire explosion and its ability to effect detonation in PETN. Detonations could not

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*This is idealized because each diameter wire would produce a trace somewhat different from the traces for other diameter wires. This occurs because of the differences in wire resistance and minor changes in wire inductance.

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be effected with the 0.0005-, 0.004-, and 0.005-inch diameter wires. Detonation was effected by the 0.001-, 0.0015-, 0.002-, and 0.003-inch diameter wires. The ordering, based on the ability of the wire to initiate the least sensitive PETN, shows the 0.002-inch diameter wire to be most effective followed by the 0.0015-, 0.003-, and 0.001-inch diameter wires, in that order. Comparison of this ordering with that observed in air is given below:

Ordering of Wire Diameter (inches)

To Effect Detonation in PETN	Vigor of Exploding Wires in Air
1. 0.002	0.003
2. 0.0015	0.002
3. 0.003	0.0015
4. 0.001	0.001

The wire with the most vigorous output in air is not the best for effecting detonation when surrounded by PETN. Voltage and current oscillograms obtained on the 0.003-inch diameter wire (see Figure 8) show that the current pulse dropped off rapidly when the wire exploded in contact with PETN as compared to the wire exploded in air. Wires less than 0.003-inch in diameter retain the resurge. It appears that energy of electrical origin in the interval just after the wire burst can be beneficial in effecting detonation. Previously, it was not known if events up to the time of wire explosion or up to the time detonation appeared (about one microsecond later) were important.

DISCUSSION

11. The existence of an optimum wire diameter can be rationalized on the basis that very thin wires are poorly matched to the firing circuit. Thin wires explode in short times using a small quantity of the available stored energy during the interval of importance (time to burst plus approximately one microsecond). If the wire diameter is too large, the wire will not absorb sufficient energy to cause vaporization. This occurs even though the stored energy is sufficient to completely vaporize the wire. A comparison of energy deposition into the various diameter wires is shown in Figure 9. Energy deposition is more rapid initially with the thinner wires because of their higher initial resistance. Wires more nearly matched to the circuit initially absorb energy at a slightly lower rate than the thin wires and then, as their resistance increases, more rapidly than the thinner wires. The change of wire resistance with time is shown in Figure 10. The value of the peak resistance decreases with increasing wire

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diameter. The larger wires absorb energy at a lower rate.
Their resistance remains less than that inherent in the firing
circuit during the period of greatest possible energy deposition
(first half sine wave current pulse). The 0.004-inch diameter
wire absorbs sufficient energy to give a weak explosion. Both
the 0.004-and 0.005-inch diameter wires receive insufficient
energy to completely vaporize the wires and can be classified
as "Chace-Class I"[7]. The 0.005 inch diameter wire appears
visually to break into molten droplets. This breaking occurs
after the cessation of current flow since the average resistance
remains almost constant at 0.1 ohm during the period of current
flow.

12. Examination of energy deposition to time of wire burst,
energy deposition during the microsecond interval after burst,
and total energy deposition reveals no correlation with the
ability of the wire to effect detonation. See Figure 11. Also,
energy deposition in excess of that required for complete
vaporization of the wire does not correlate. Energy density at
burst shows an optimum for the 0.002-inch diameter wire which
was found best for effecting detonation in PETN. However, the
other diameter wires do not correlate with their respective
ability to effect detonation. See Figure 12. Energy density
at "burst plus one microsecond" shows that at this time the
thinner the wire, the higher the energy density*.

13. The average power and peak power for the various diameter
wires was also examined. See Figure 13. Average power does not
correlate with the ability to effect detonation, but peak power
does show a correlation. Peak power occurs almost concurrently
with the peak voltage and may indicate the most important period
of electrical energy deposition. It has already been observed
with the 0.003-inch diameter wire that energy after burst can be
beneficial, but is not absolutely necessary.

14. The shock wave emitted by the wire is normally non-luminous.
It can be rendered visible for examination by techniques such as
developed by Bennett. The shock enters both the PETN crystals
and interstitial air spaces. Examination of the air shock wave
generated by the weakest exploding wire (0.001-inch diameter) to
effect detonation reveals a velocity of 1860 meters/second. This
is for a flush mounted wire and is the velocity of the air shock
almost immediately after it becomes distinguishable from the
plasma at approximately 0.4 microsecond. Using an interpolated
value from data by R. Becker[8] a shock pressure of 0.037 kilobar
is calculated.

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*Assuming all energy remains in wire material.

15. To determine whether or not compression by the shock of air
trapped within the explosive could produce temperatures needed
for initiation, the final temperature after adiabatic compression
of a trapped gas bubble:

$$T_2 = T_1 \left[\frac{P_2}{P_1} \right]^{\frac{\gamma-1}{\gamma}}$$

where T_2 = final temperature in degrees absolute

T_1 = initial temperature in degrees absolute

P_1 = initial pressure in bubble

P_2 = final pressure in bubble

γ = ratio of specific heats

was calculated. The calculation shows that a temperature of
550°C can occur in the gas bubble under the experimental
conditions. This is above the minimum temperature rise of 450°C
calculated by Bowden and Yoffe[9] as necessary for initiation to
occur. However, experiments by both Cachia and Whitbread[10], and
Seay and Seely, Jr.[11] indicate that interstitial air has no
effect on the shock initiation of loosely packed granular, PETN.
Cachia and Whitbread, employing a gap test, found that the
critical gap remains the same whether or not interstitial air is
present. Seay and Seely, using the wedge test, also found that
the removal of interstitial air did not affect initiation. When
they replaced interstitial air in a low density PETN with argon
(for high temperatures) and methane (for low temperatures), it
was found that the temperature of the interstitial gas had
nothing to do with the mechanism of initiation. Their experi-
ments further showed that a 2.5 kilobar shock pressure in the
PETN pressing was barely sufficient to initiate granular PETN at
a density of 1.0 g/cm³. A shock wave of the pressure encountered
in the wire explosion is roughly two orders of magnitude lower
than the value given by Seay and Seely. It thus appears that
the shock wave is not the primary cause of initiation. It also
appears that if the shock wave plays any role in the initiation
it is through the medium of the PETN crystals and voids and not
the interstitial gas. The largely unknown possibility of shock
reflections and interactions due to interstitial spaces, crystal
imperfections, and crystal voids preclude a definite conclusion
on the role of the shock wave at this time.

16. It was noticed that the best firing time reproducibility is
obtained when the wire explodes on the initial portion of the
current pulse. The length of the block rectangle in Figure 6
indicates the time spread for each wire size.

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17. It appears that the diameter of the wire should be chosen so as to explode on that portion of the current pulse best suited to give the desired effect. See Figure 14. If time reproducibility is the main consideration, the wire should explode in region A with enough of a safety factor to insure detonation. If general functioning reliability is the main consideration, region B should be chosen. If maximum wire output is desired (i.e., to break diaphragms, etc.), region C should be chosen.

CONCLUSIONS

1. The diameter of an exploding wire can be chosen so as to favor time reproducibility of explosion, reliability of effecting detonation, or vigor of the bridgewire output.

2. The wire with the most vigorous output in air is not necessarily the most efficient for effecting detonation in PETN.

3. Relatively thin and thick diameter wires are unable to effect detonation in PETN with the fixed value firing circuit components and voltages used.

4. For various diameter wires of constant length, peak power shows a correlation with the ability of the wire to effect detonation.

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10. Cachia, G. P., and Whitbread, E. G., "The Initiation of Explosives by Shock", Proc. Roy. Soc. A246, No. 1245, July 1958.

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TABLE 1

Effect of Wire Diameter

Wire Diameter (inch)	Density of PETN (g/cm³)																	
	0.7		0.8		0.9		1.0		1.1		1.125		1.15		1.175		1.2	
	D	L	D	L	D	L	D	L	D	L	D	L	D	L	D	L	D	L
0.0005	0	3	0	2	0	2	2	2										
0.001			2	0	2	0	2	0	0	2								
0.0015			2	0	2	0	2	0	2	0	3	1	3	3	0	2	0	2
0.002			2	0	2	0	2	0	2	0	4	0	5	1	0	2	0	2
0.003			2	0	2	0	2	0	2	0	3	1	0	6	0	2	0	2
0.004			0	2	0	2	2	2										
0.005			0	2	0	2	2	2										

D = Detonation

L = Low order

R_1 — 5 MEG

R_2, R_3 — VOLTAGE DIVIDER

R_4 — CURRENT SHUNT
(0.0102 OHM)

FIRING CHAMBER

R_2

EBW

8"RG-58/U

R_4

R_3

TO DUAL BEAM
OSCILLOSCOPE

POWER SUPPLY

0.97 MFD

20"RG-58/U

R_1

GL 7964

FIG. I TEST CIRCUIT

FRONT SILVERED MIRROR

TO PULSER

CONTACT
SURFACE

SHOCK WAVE

8 CM

CONTACT
PIN

TIME

SUPPORT
POST

WIRE
MOUNT

OPTICAL   AXIS OF
SMEAR   CAMERA
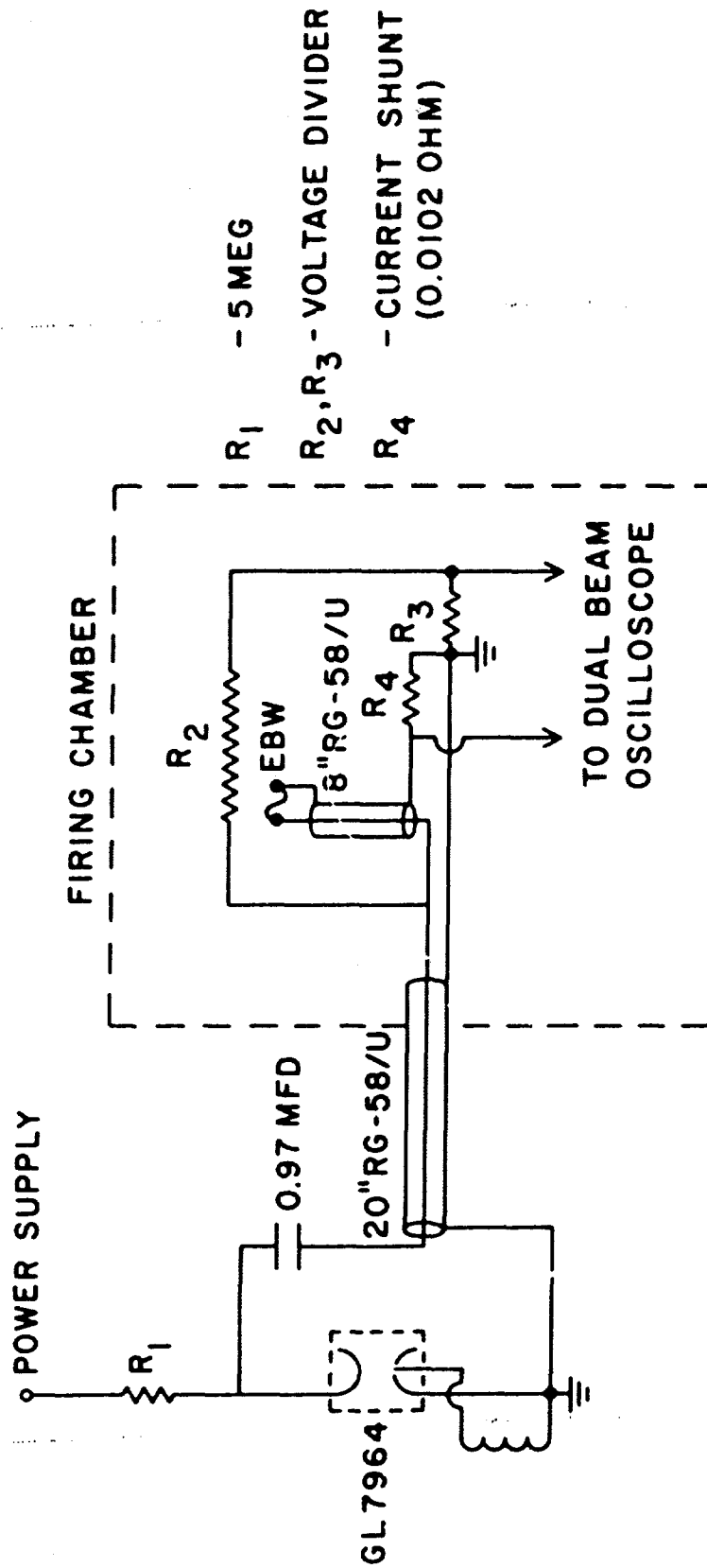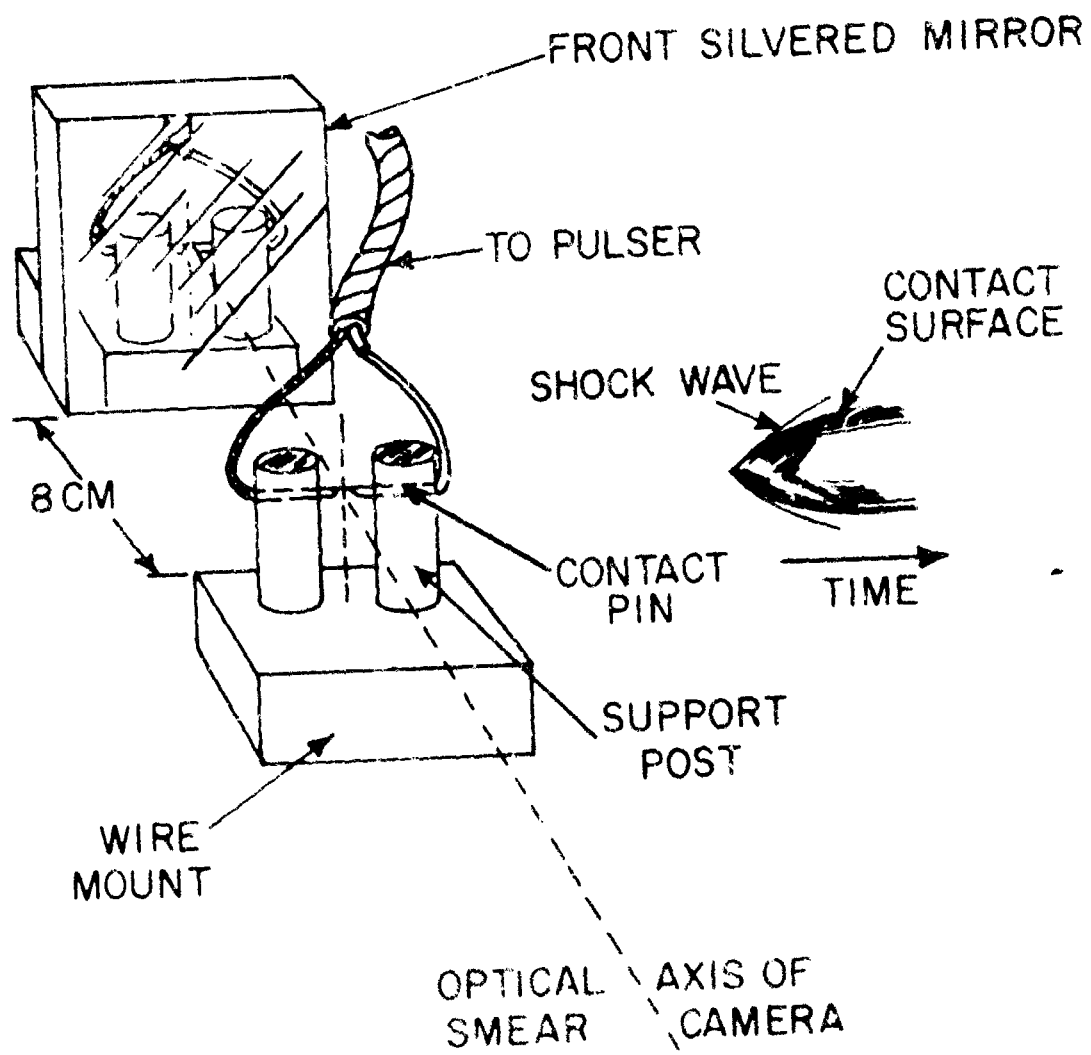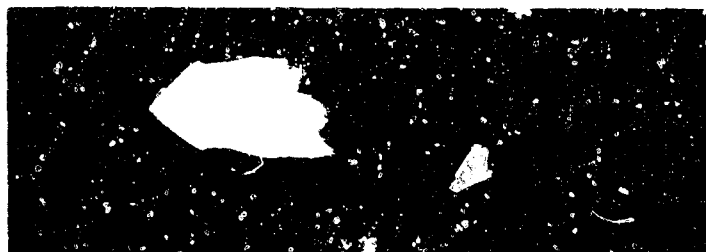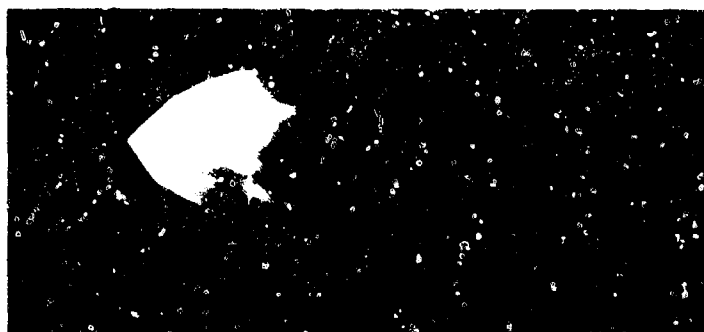
FIG 2 TEST ARRANGEMENT

0".001

0".003

0".004

0".005

0 2 4 6

MICROSECONDS

ICM.

FIG 3 SMEAR CAMERA RECORDS OF VARIOUS DIAMETER
WIRES IN AIR
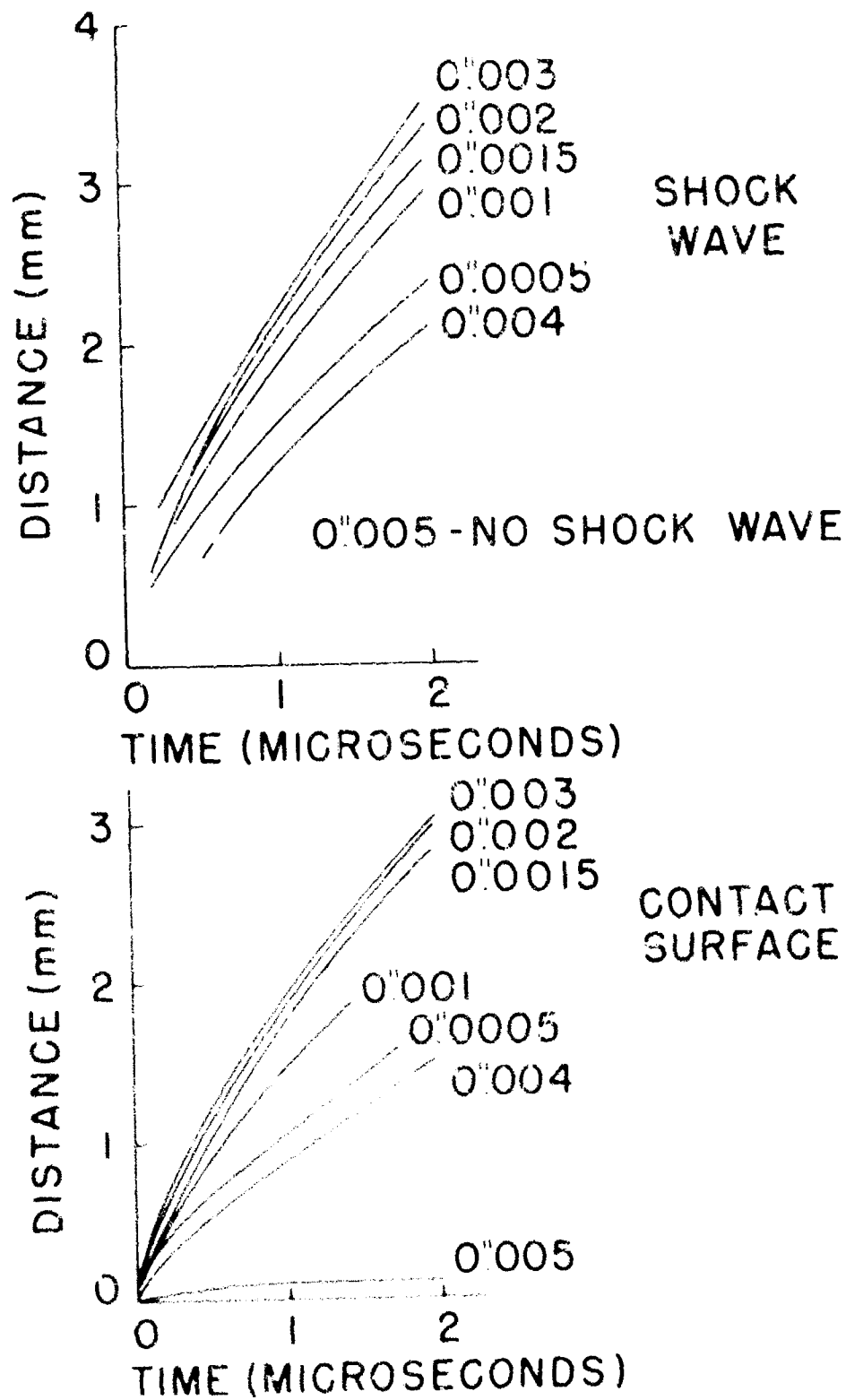
FIG. 4 PHOTOGRAPHIC OUTPUT COMPARISON OF
SUSPENDED WIRES IN AIR
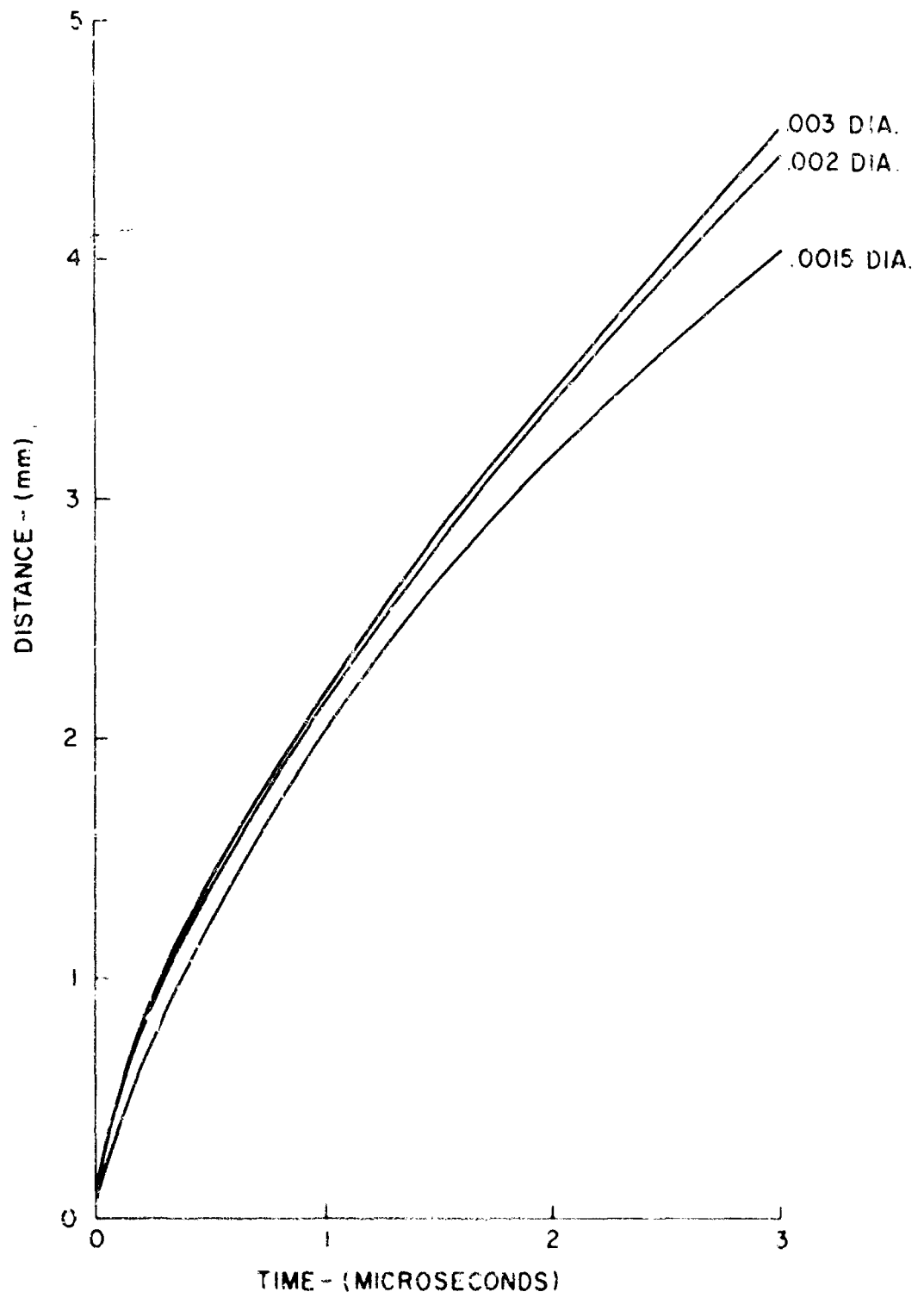
FIG.5 PHOTOGRAPHIC OUTPUT COMPARISON OF FLUSH
MOUNTED WIRES IN AIR
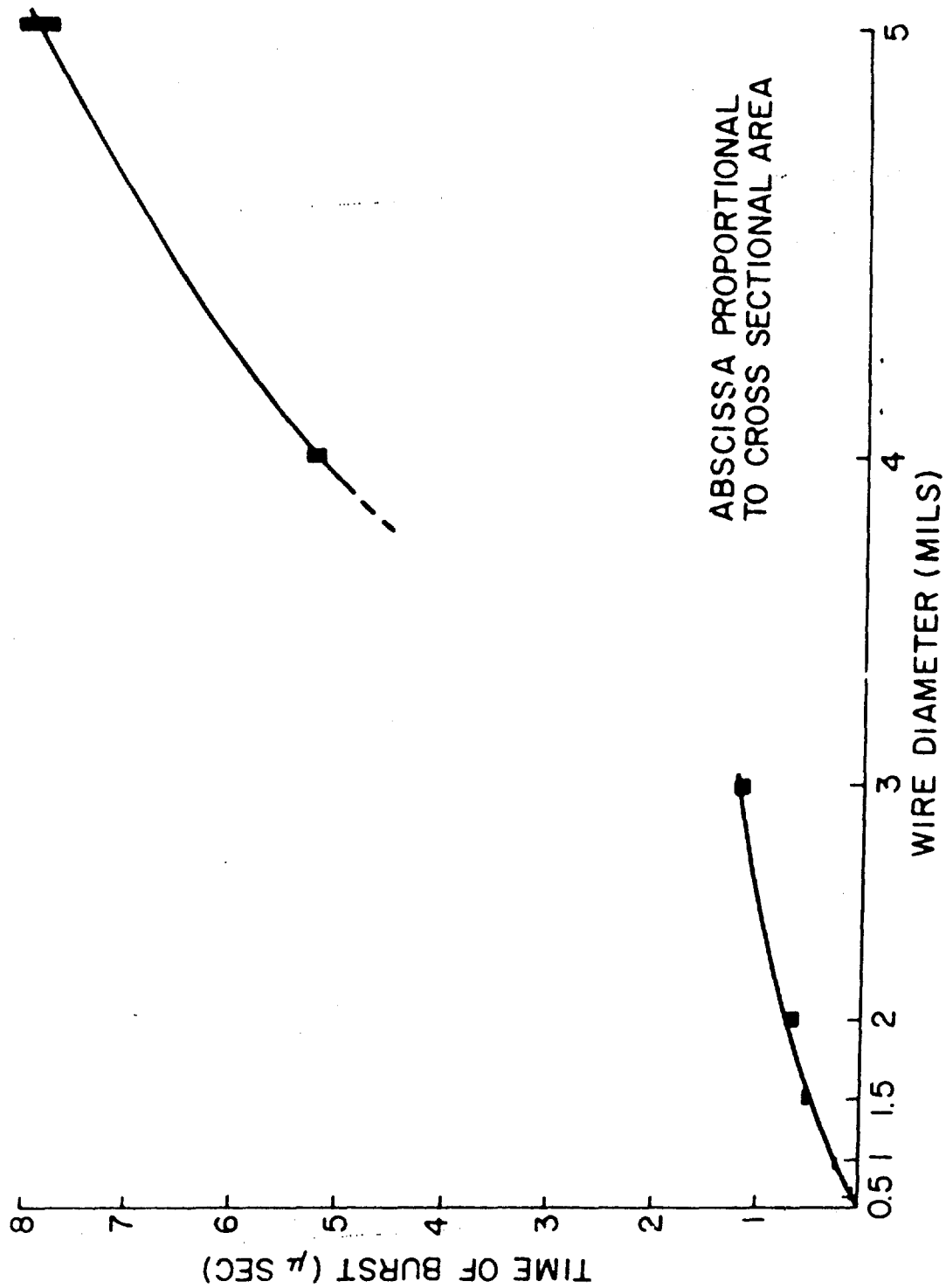
FIG.6 TIME OF BURST VS. WIRE DIAMETER IN AIR
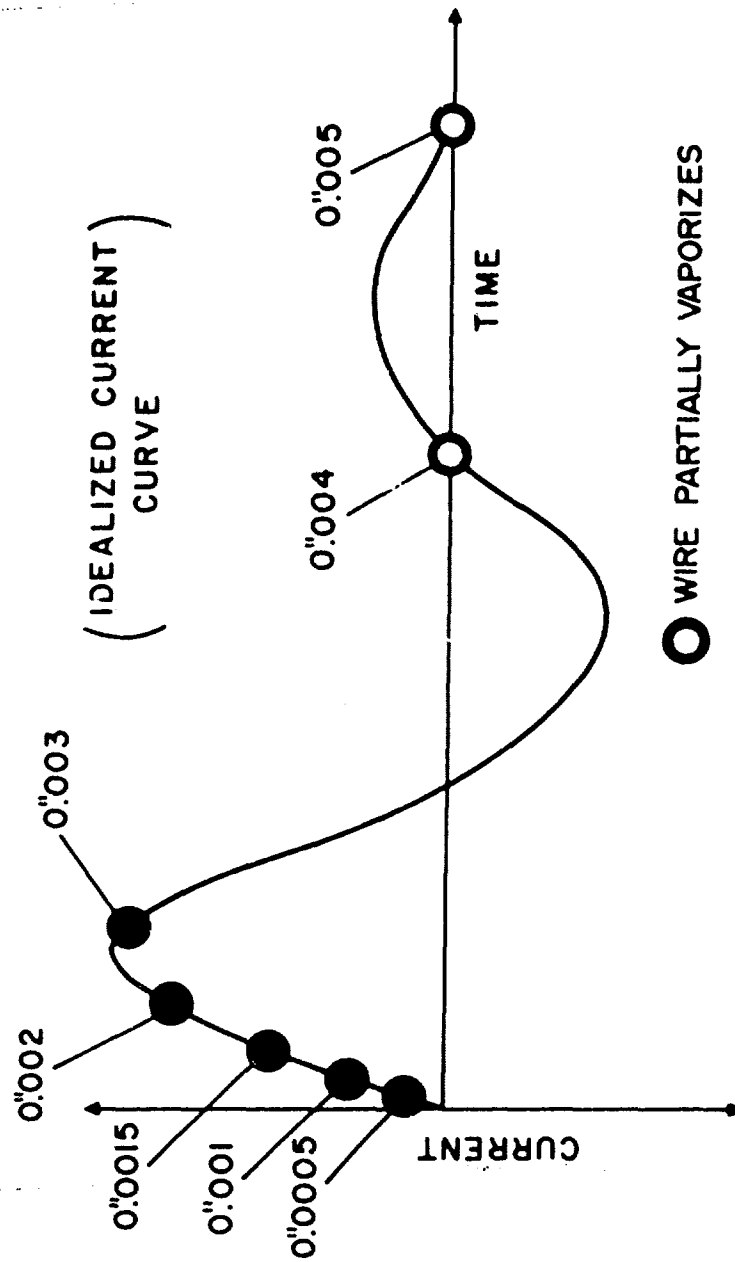
FIG. 7 EXPLOSION LOCI OF VARIOUS DIAMETER WIRES IN AIR

WIRE SUSPENDED IN AIR

SWEEP-0.5μSEC/DIV
POTENTIAL-1000 VOLTS/DIV
CURRENT-490 AMPS/DIV

◄────── TIME

WIRE IN EXPLOSIVE TEST
FIXTURE

FIG. 8 OSCILLOGRAMS OF 0".003 DIAMETER PLATINUM WIRE

FIG. 9 ENERGY DEPOSITION VS TIME
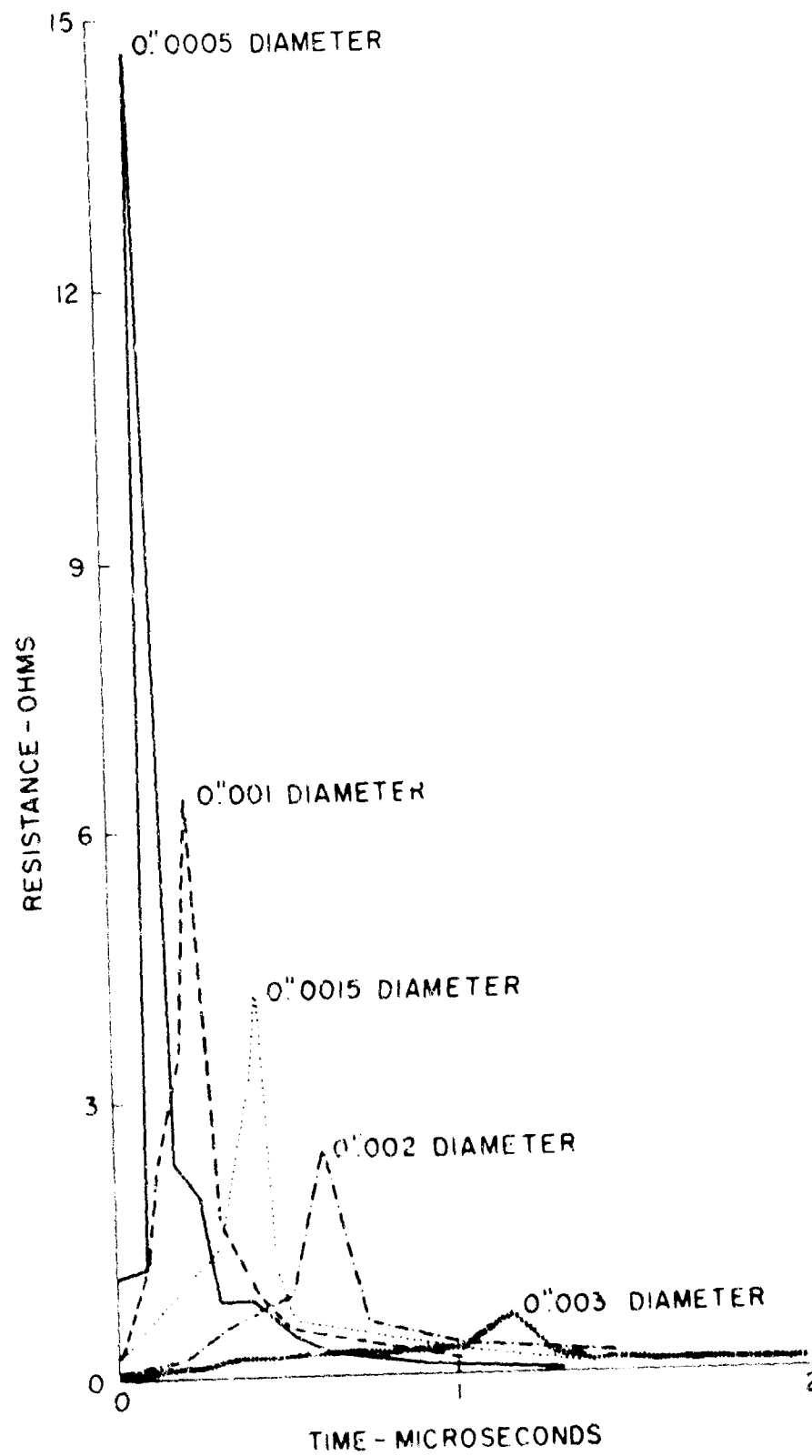
FIG. 10 VARIATION OF WIRE RESISTANCE WITH
TIME
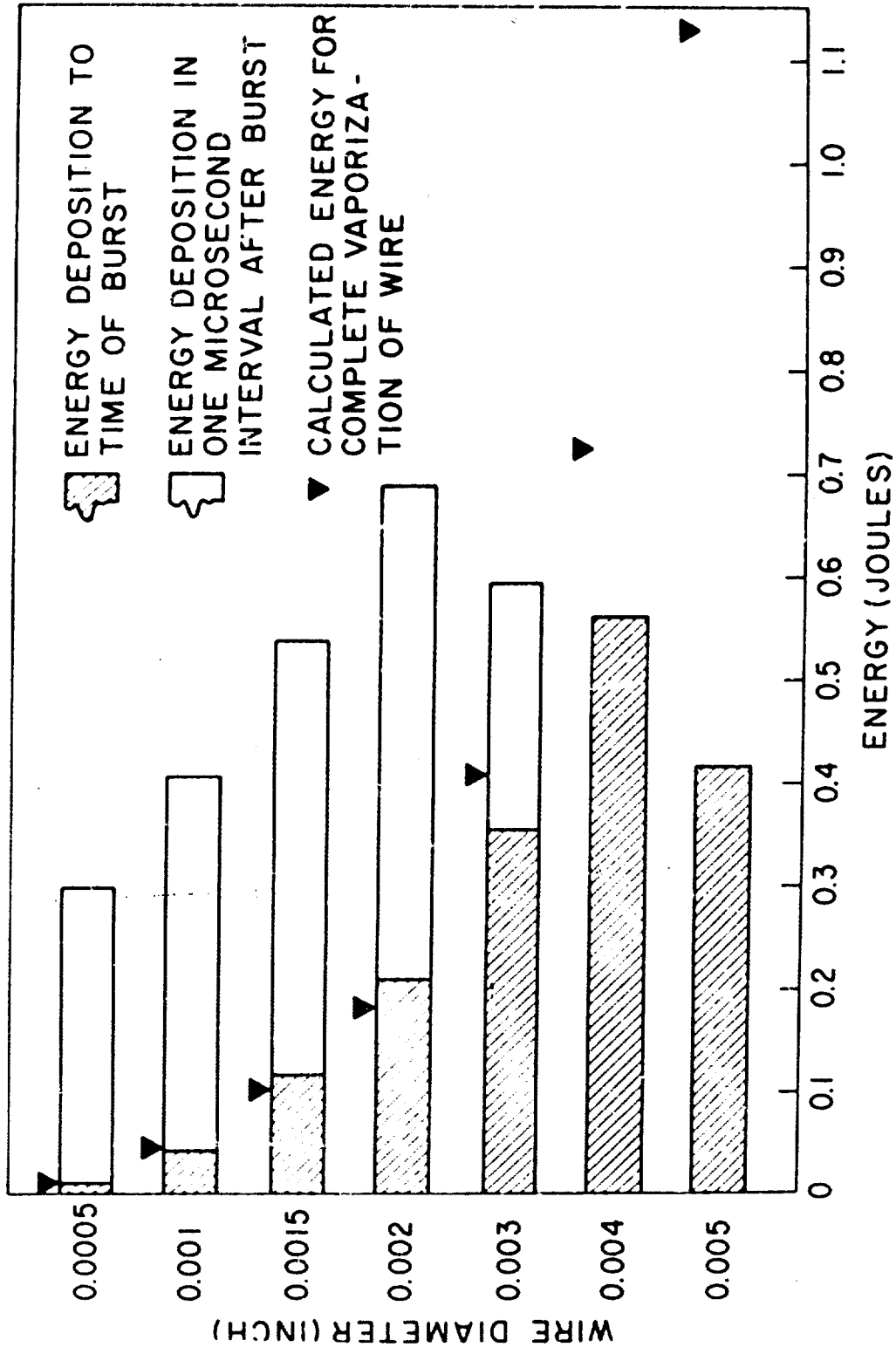
FIG.II ENERGY DEPOSITION
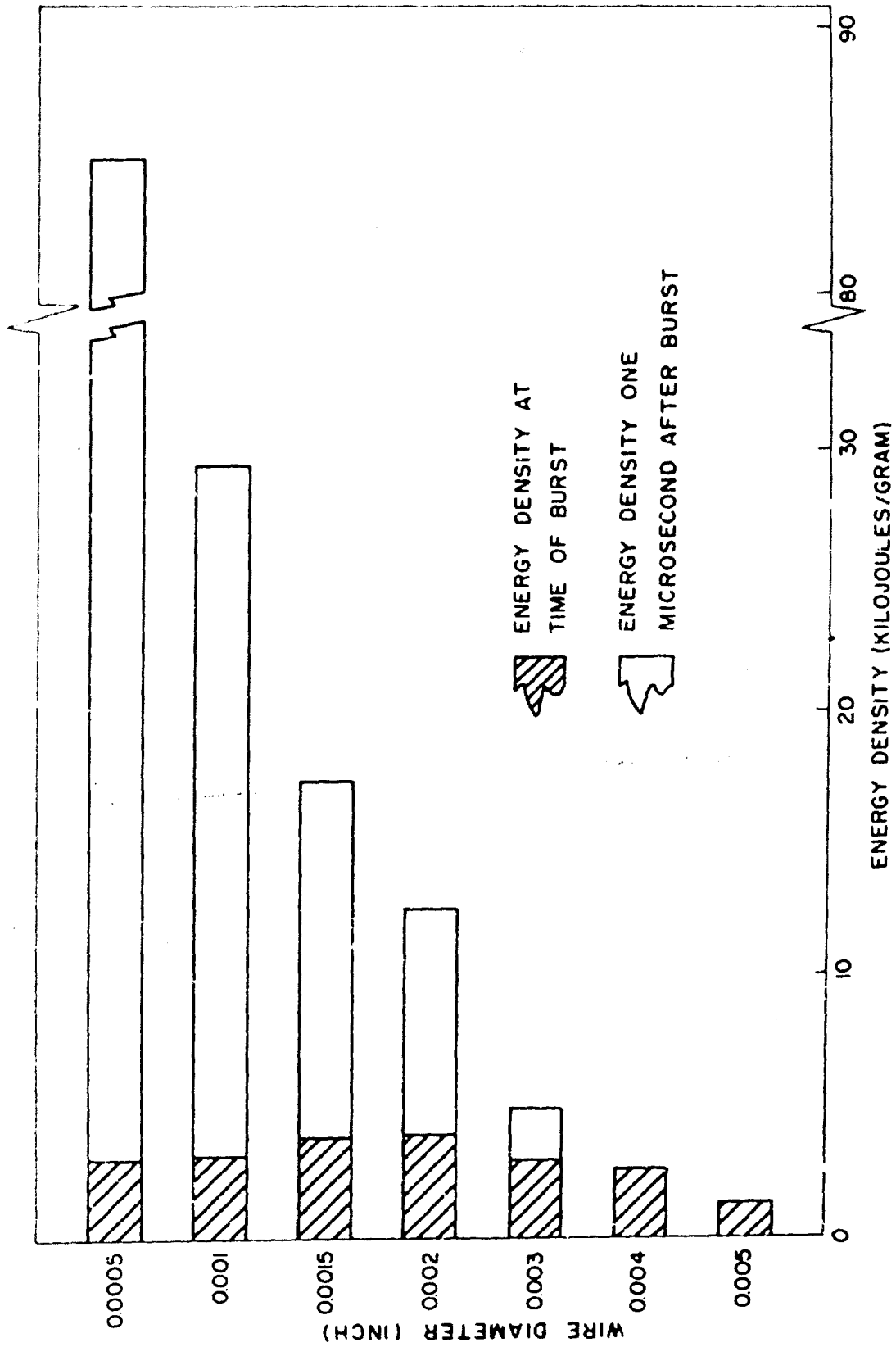
FIG. 12 ENERGY DENSITY
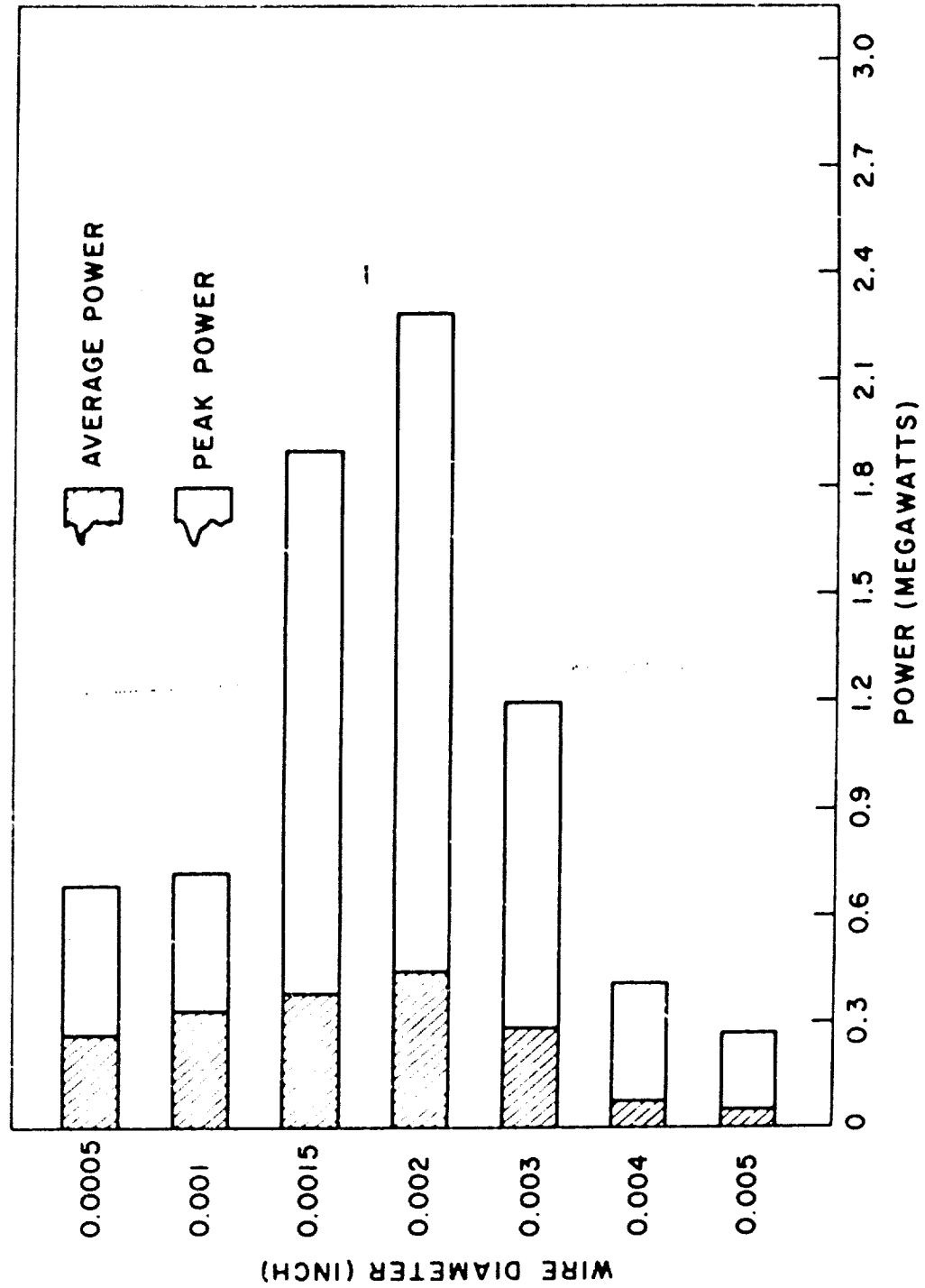
FIG.13 PEAK AND AVERAGE POWER

A—OPTIMUM TIME REPRODUCIBILITY
B—OPTIMUM FUNCTIONING RELIABILITY
C—OPTIMUM WIRE OUTPUT
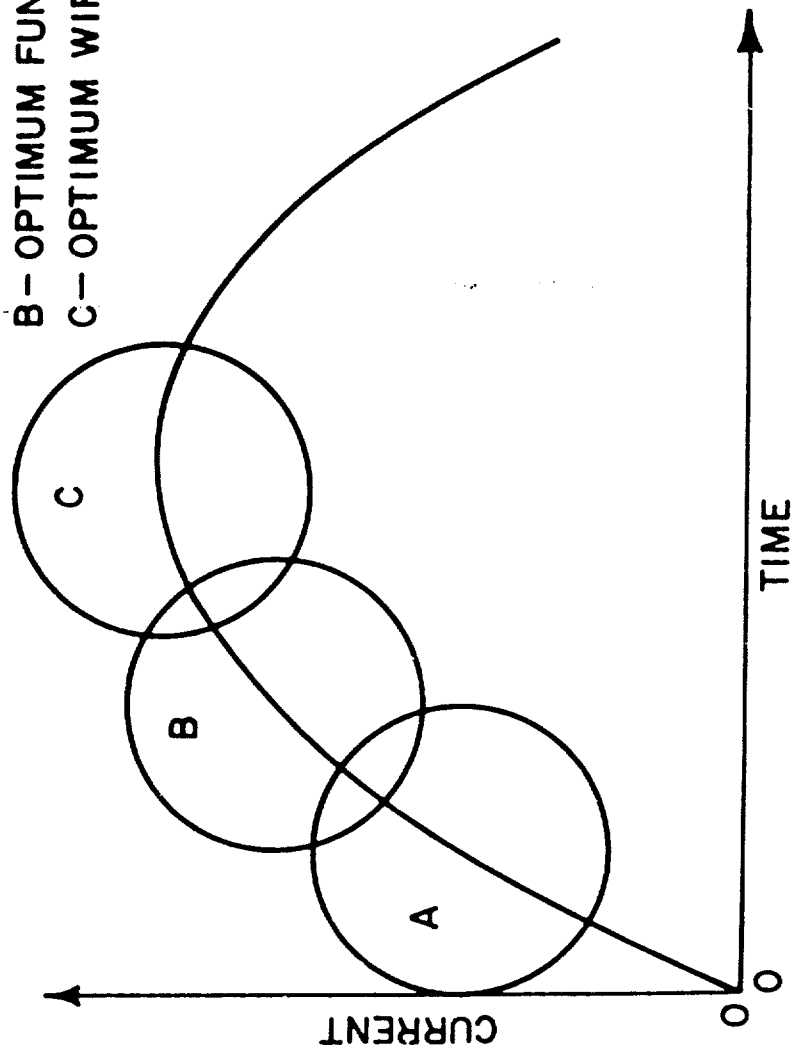
FIG. 14 REGIONS OF WIRE EXPLOSION

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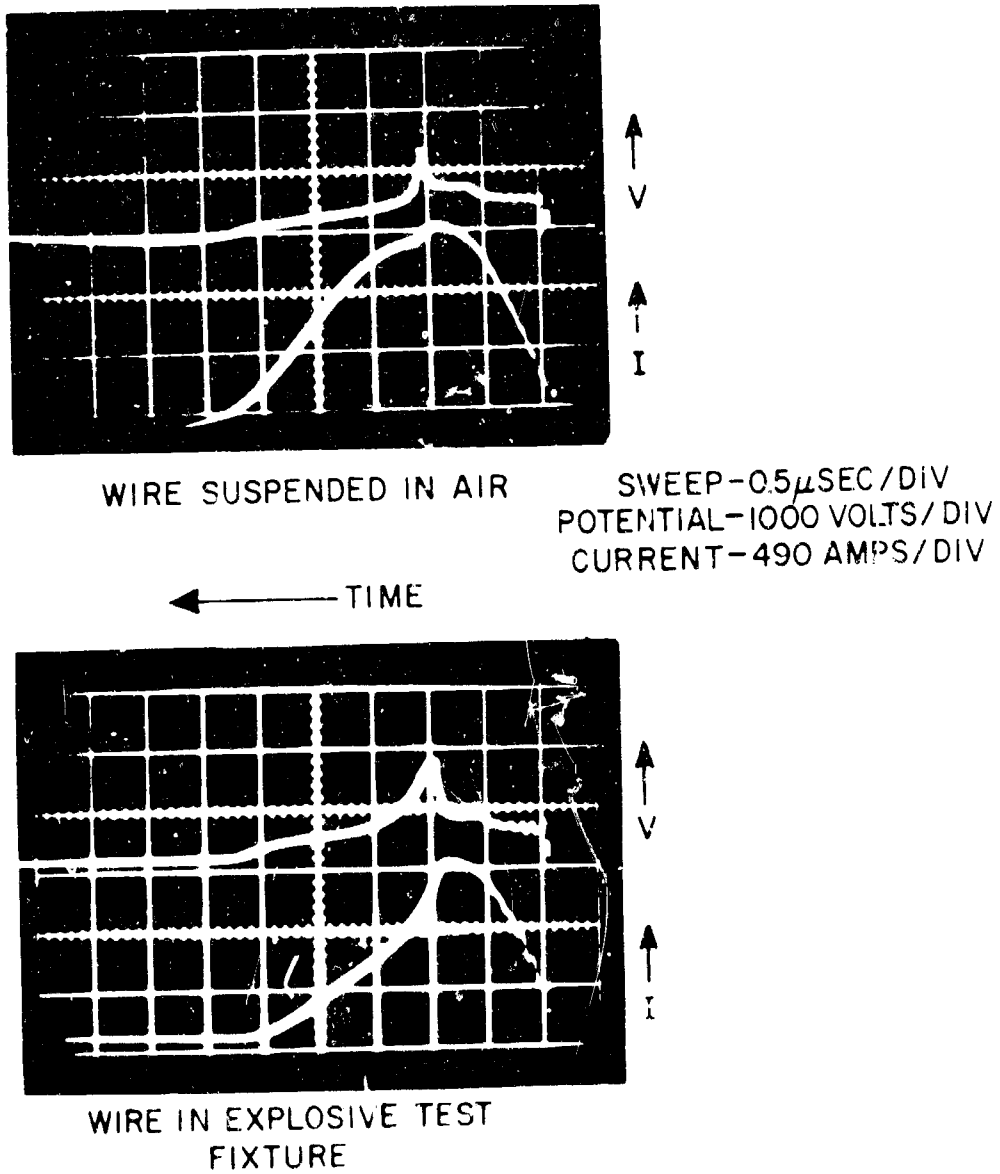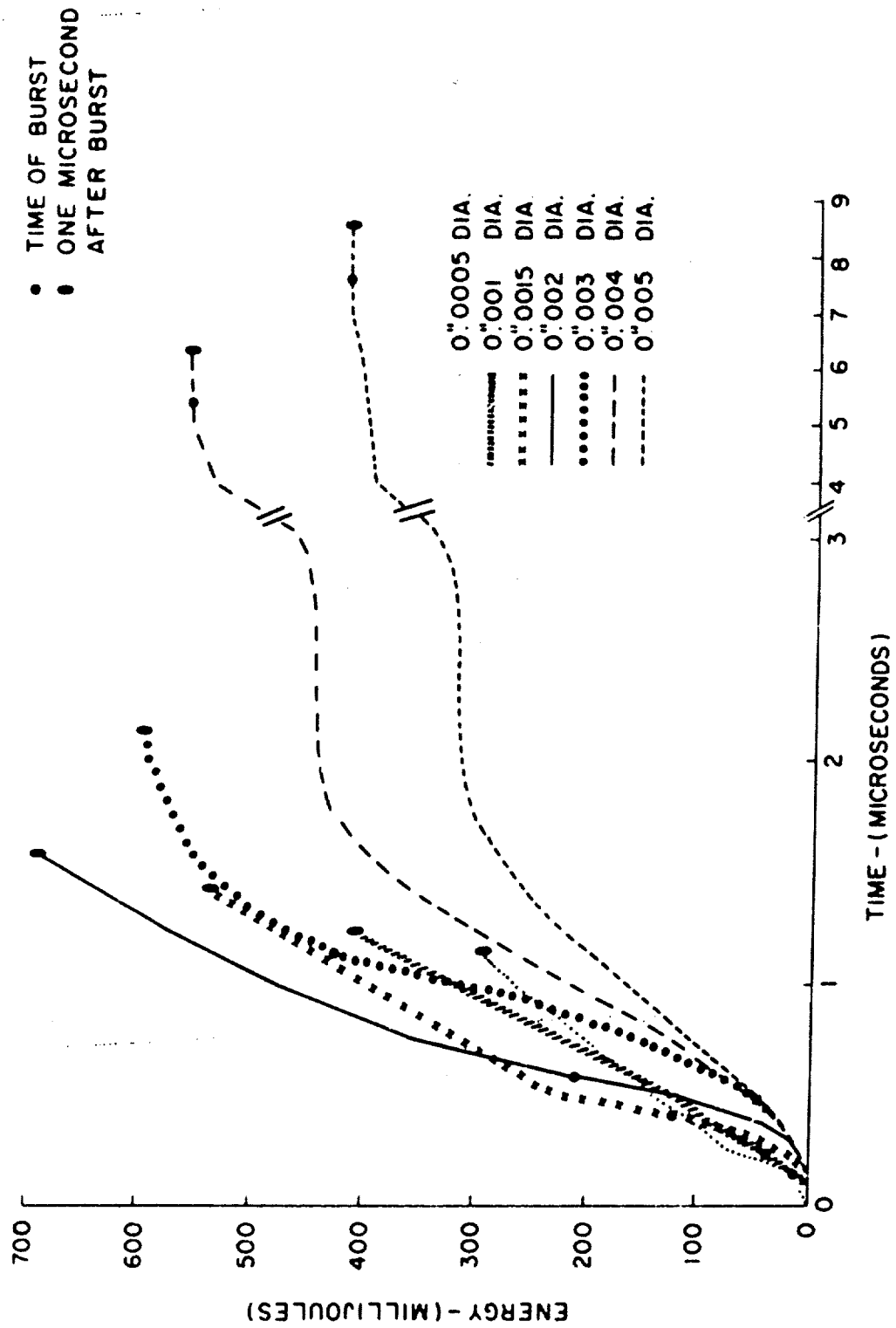|	
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	DESCRIPTORS	CODES	DESCRIPTORS	CODES
SOURCE	NOL technical report	NOLTR	Unclassified – 26	U∅26
REPORT NUMBER	64-2	64∅∅∅2		
REPORT DATE	17 March 1964	∅364		
SECURITY CLASSIFICATION AND CODE COUNT				
CIRCULATION LIMITATION				
CIRCULATION LIMITATION OR BIBLIOGRAPHIC				
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SUBJECT ANALYSIS OF REPORT

DESCRIPTORS	CODES	DESCRIPTORS	CODES	DESCRIPTORS	CODES
Initiation	INTI	Energy	ENER	Circuitry	CIRC
Explosives	EXPL	Source	SOUR	Test procedure	TESI
Exploding	EXPI	Time	TIME		
Wires	WIRE	Reproducibility	RERO		
Effect	EFFE	Explosion	EXPS		
Diameter	DIAM	Reliability	RELI		
Penta	PENA	Detonation	DETO		
Erythritol	ERYT	Stength	STRN		
Tetra	TERA	Bridge	BRID		
Nitrate	NITT	Output	OUTP		
Platinum	PLAU	Shock	SHOC		
Capacitor	CAPA	Electrical	ELEC		

PMC-NOL-S78/78 (1-62)

Naval Ordnance Laboratory, White Oak, Md.
(NOL technical report 64-2)
INITIATION OF EXPLOSIVES BY EXPLODING
WIRES. III. EFFECT OF WIRE DIAMETER ON THE
INITIATION OF PETN BY EXPLODING WIRES, by
Howard S. Leopold. 17 Mar. 1964. 9p, il-
lus., tables. Bureps task RUME-4E000/212-1/
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UNCLASSIFIED

The effect of wire diameter on the initi-
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was investigated. The diameter of the wire
can be chosen so as to favor time reproduci-
bility of explosion, reliability of effecting
detonation, or vigor of the bridgewire output. Abstract card is
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1. Explosive-
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